Can Spacetime Help Settle Any Issues in Modern Philosophy?*

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1 Introduction

Deciding what to talk about in this paper was a challenge; perhaps contemporary philosophy offers no more possible topics to choose from than any of the individual figures considered over these two days, but what to present that might connect the historical papers with contemporary philosophy? How to say something that might be informative and substantive and useful to an audience which likely comes from a historical background? One option was to discuss philosophical issues concerning contemporary spacetime physics – quantum gravity and string theory say. While that approach might show something of how philosophy continues to engage with emerging science, the danger is that attempts to relate such issues to historical concerns will be forced.

I've opted instead to discuss a few influential ideas about how twentieth century mathematics and philosophy can help understand and resolve early modern questions about the nature of space and time. In part I'll be offering a map of the issues; I'll be covering quite a lot of ground in a small time, but presumably it's not entirely new to this audience. To be substantive as well as informative, I want to engage with the ideas I discuss. In particular, (i) I want to explore the limits of the mathematical theory of spacetime (more generally, differential geometry) *as an analytical tool for interpreting early modern thought.* While it dramatically clarifies some issues, it can also lead to misunderstandings of some of the figures that we have been considering here, and is a very poor tool indeed for others – Leibniz in particular. (ii) I will show how to blunt a very influential argument against a 'relational' conception of spacetime – the view that the properties and relations of bodies exhaust the spatiotemporal.

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There are two flaws in this paper that I wish to acknowledge from the outset. The first is that time constraints have forced me to bracket important contributions to the debate, notably, Friedman (1983); ultimately because that work is less concerned to use the spacetime formalism to do history of philosophy, and it doesn't take me as directly to the substantive points I wish to make. The second flaw is that some of my criticisms of contemporary philosophers seem like nit-picking compared to the critiques that they made of their predecessors – in particular, my critique of the spacetime approach is within the tradition initiated by Stein *et al*, not a break from it. Still, I believe that an investigation of the limitations of that approach is timely and useful.

2 Spacetime and Historiography

Howard Stein's 1967 essay transformed the understanding of the so-called 'absolute-relative' debate within the philosophy of physics community (though probably not entirely in ways Stein desired). In particular, the use of the spacetime framework became, perhaps, the most important tool for those seeking to analyse the contributions of historical figures to the debate. In this section I want to describe some of the ways in which that tool has been used, attempting to distinguish the uses which are genuinely illuminating from those that are misleading.

(Since I posted a draft of this paper, I have received some illuminating correspondence from Stein, for which I am very grateful. As a result I have made certain changes. Some are minor, while a couple are more significant regarding Stein's intentions [but not my central concern with the limitations of the spacetime approach]. Some require further clarification, and in no case can I guarantee that I have not traded one misinterpretation for another.)

2.1 Newton

Stein's paper is multifaceted, but for our purposes, the crucial points are as follows: first, Newton's postulation of absolute space and time can be understood in terms of a spacetime with the geometry of the Cartesian product of a three-dimensional and a one-dimensional Euclidean space, $S \times T$. The crucial feature of the Cartesian product is that it induces projections of any event onto 'simultaneous' and 'spatially coincident' events: in particular, if a point of $S \times T$ is denoted $p = (\sigma, \tau)$, then the points (σ, t) for any $t \in T$ are spatially coincident with p. According to Stein, Newton's postulation of absolute time amounts to the postulation of T. But absolute space is the space of equivalence classes of coincident points, which itself has a natural three-dimensional Euclidean geometry. That is, absolute space is not simply S, but S *in the spacetime* $S \times T$, in order to capture the idea of the persistence of spatial points through time.[1]

[1]Of course Newton implicitly takes absolute time to be 'spread through' space: simultaneity is absolute. In this sense absolute time is similarly not merely T, but the space of equivalence classes of simultaneous points, which itself has the same geometry as T. It is T in $S \times T$.

$S \times T$ – which we shall call 'Newtonian' spacetime (*contrary to Stein's usage*) – makes absolute velocity well-defined; it is the velocity relative to the points of absolute space. And since absolute velocity is well-defined, so is absolute acceleration; indeed, Newton introduces the structure precisely because the latter quantity is required by his mechanics. But, as Newton's *Corollary V* to the laws makes clear, the models of Newton's laws are independent of absolute velocity; as far as the laws are concerned, the concept has no content. The 'solution' – not Newton's, of course – is to apply a kinematical principle of 'Galilean relativity': view the natural spatial projection in $S \times T$ as a representational artefact, and treat all projections at a constant angle to it – all 'straight' ones – as equivalent. This 'Galilean' spacetime lacks the structure to reidentify points over time – no one projection is singled out as the correct one – and so does not support a well-defined quantity of absolute velocity. (Put another way, instead of a relation of spatial coincidence between pairs of non-simultaneous events, in Galilean spacetime there is a relation of colinearity between triples of points.) However, it is a simple but important fact that the acceleration of a body relative to the points identified by the natural projection is the same as its acceleration relative to the points identified by any straight projection; put another way, accelerations reckoned in one frame are equal to the accelerations in any other frame in constant, linear relative motion. *Thus in Galilean spacetime there is a well-defined notion of absolute acceleration, but not of absolute velocity*; it satisfies the kinematical presuppositions of Newtonian mechanics, without introducing unobservable motive quantities.[2] Thus Galilean spacetime address a long-standing objection to Newton's account of motion.

Using the spacetime framework, Stein's paper makes a number of important points. In particular, he explains how Newton's 'metaphysical' speculations concerning absolute space and time can be logically separated from his 'scientific' discussions. On the one hand we have the ideas that space is 'as it were' God's sensorium (*Optiks, Query* 28) or an 'emanative effect of God' (*De Gravitatione*). On the other, such remarks are absent from the *Principia*; moreover, absolute quantities of motion are in no way superfluous to mechanics. In the spacetime framework, with a $1/r^2$ force, it is indeed the case that the planets orbit the Sun (or rather the centre of mass of the solar system); in the sense given by the geometrical framework of either spacetime, the planets accelerate towards the Sun, not the Earth. Such quantities are crucial to Newton's project, and can be inferred from empirical phenomena – the observed motions of the planets; so insofar as absolute space is postulated to make them well-defined, it is scientifically respectable. (Of course, absolute space is still unempirical insofar as it makes absolute velocity well-defined; but Newton's 'error' is not wilful deviation from scientific methodology, but failure to see how else to define absolute acceleration.)

[2] Actually, in a sense it doesn't. As Newton demonstrated in *Corollary VI*, a system is indistinguishable from any other that differs only in a common acceleration of its parts: for instance, a closed system in inertial motion is indistinguishable from an identical system in free-fall. Perhaps one should conclude that the 'common acceleration of the whole' is not a well-defined quantity either; but it is well-defined in Galilean spacetime and *prima facie* by Newton's laws – the systems experience different forces.

More generally, Stein wishes to show that Newton's analysis in the *Scholium* (to the *Definitions*) vindicates his postulation there of absolute space and time. That is, the *Scholium* is not a gratuitous metaphysical intrusion in the *Principia*, but demonstrates the failure of 'purely relative' definitions of motion to agree with the concept of motion in mechanics, and uses those laws to investigate the empirical content of Newton's concepts of motion.

In Stein's view, the vindication of absolute quantities requires only that Newton's definitions of 'absolute' concepts are clear and that they allow the formulation of true, substantial, *empirical* propositions.[3] That is, they require a positive analysis of their 'empirical content'. If in this sense the structure of absolute space and time are exhibited by mechanical events, then any further investigation of the metaphysics or ontology of spacetime is 'supererogatory'.[4] Stein doesn't say explicitly what he takes Newton's definitions to be, but rather that terms such as 'absolute rotation' have meanings within mechanics. One way to formulate such a claim is by the idea that the concepts are defined implicitly by the laws. For instance, perhaps they could be defined in accord with the Carnap-Lewis account of the definition of theoretical terms (e.g., Lewis 1970). Rather schematically, let N[motion] be Newton's laws, and N[x] the laws with every occurrence of the term 'motion' replaced by the free variable x; then 'absolute motion' is defined to be '*the* x such that N[x]'. The spacetime framework allows a clear and precise statement of the formal properties of motion thus defined; it possess all the properties of motion in Galilean spacetime (and no more).

Let me make a few remarks about my suggested formulation. First, it is no part of Lewis' account that such a definition is an 'empirical' one, in terms of vocabulary privileged in some epistemologically foundational way; rather the definitions are given in terms of whatever terms are understood prior to the new theory. Thus I am not proposing that Stein's Newton defines absolute rotation in terms of what can be observed in a bucket of water or about the tension in a rod between two spheres – that Newton's empirical analysis of the concepts is itself a definition. One might still ask whether all definitions terminate in empirical ones: is there a chain of Carnap-Lewis definitions that eventually leaves only empirical terms undefined? Lewis' account is simply not aimed at offering a

[3]In correspondence, Stein denied that Newton defines absolute space and time. However, he asks (1967, 195) 'not whether space, time, and motion really are as [Newton] takes them to be, but whether his definitions make sense'. I believe that what Stein's denial means – in the first place – is that Newton's empirical analysis of the concepts is not itself a definition of them. The gloss on Stein that I develop immediately below is compatible with that part of his view. However, when DiSalle (2002, 2006) claims that Stein's Newton is defining absolute concepts, it seems to me that he does mean that the empirical analysis is the *definiens*; otherwise it is hard to understand his claim that *by definition* Newton can't be wrong that the water in the bucket is in absolute rotation (2002, 44). I should add that DiSalle's work on Stein pushed me to think more carefully about it than I had in the past.

[4]For Stein, some of Newton's views concerning space are supererogatory in this sense, but not – absolute velocity aside – those in the *Scholium*. Contrary to what I suggested in the earlier draft, Stein does not claim that such views are meaningless or 'ill-posed'.

general theory of meaning, but rather at showing how new terms can obtain meaning from old terms and new theory. All that is important in the present case, is that somewhere in the chain are terms with empirical meaning; for that makes the analysis of the empirical content of absolute quantities a non-trivial enterprise – i.e., they have some! Finally, it is not even crucial here that the proposed schema be understood as a 'definition' in any very formal or essentialist sense of that word; it is simply a story of how we understand absolute quantities, prior to the kind of empirical analysis that Stein's Newton carries out in the *Principia*.

According to Stein, the *Scholium* shows that Newton's definitions work as required (putting aside absolute velocity); in particular, the laws entail that absolute rotations, as defined, are universally associated with centrifugal effects – an association empirically demonstrated by the bucket, just as much as the motions of the planets demonstrate the presence of a gravitational force.[5] Thus insofar as absolute space and time are postulated to define such quantities – insofar as they are the Galilean 'structure' exhibited by events – their postulation is vindicated, without any 'supererogatory' speculations about their ontological status.

Stein seems to me to be completely correct that Newton held absolute concepts to have empirical content in the senses described, and that he downplayed metaphysical considerations of space in the *Principia*. Stein was also the first contemporary philosopher to recognise that Newton's target in the *Scholium* was Descartes (though he does not discuss those arguments, instead citing *De Gravitatione*). Further, Newton did indeed understand that a stronger structure, such as the geometry of $S \times T$ was required for an adequate kinematics. All these points are very important and properly revolutionised our understanding of Newton. However, they suggest something stronger: that the *Scholium* aims to completely suppress non-empirical commitments (absolute velocity aside). To be fair, Stein does not make this claim explicitly, and from his correspondence I suspect he did not intend such a view. Nevertheless, it seems to me to be at least a natural extension of the 1967 paper (and one which DiSalle has also found), and certainly interesting in its own right. However, it takes the analysis too far.

In the first place, the definition that I have proposed only defines absolute acceleration (and rotation), not absolute space and time. So where do they come in? Perhaps Newton means that the concept defined by the laws has all the properties of motions in absolute space and time? But that would be a rather implausible gaffe: Newton knew that absolute velocity was well-defined in absolute space and also, in *Corollary V*, that such a quantity is not well-defined by his laws. (Not to mention the fact that Newton describes absolute motion as *being* motion with respect to the parts of absolute space – not merely isomorphic to it.) So perhaps instead Newton (naturally) assumed that the concept of 'motion' required a notion of change of position, and defined absolute motion as '*the motion x* such that $\mathrm{N}[x]$':

[5] Stein in fact analyses Foucault's experiment and compares it with Cavendish's, which is an oddly anachronistic strategy for reading Newton. Presumably he intends the same kind of points to hold for the experiments Newton does describe.

he defined something that after all requires the full structure of Newtonian spacetime. But now I now fear that we cannot be so sure that Newton rejected 'supererogatory' speculations about the ontology of space and time, for we cannot be sure what else he assumed was built into the concept of 'motion' – change of position relative to a substance-like object perhaps?

Newton's views on the ontology of space and time in the *Scholium* are definitely thin (especially compared to those of *De Gravitatione* and *The Optiks*). In some sense independent of bodies certainly, but what more? What I would say is that, unless some explicit indication to the contrary is given, then when someone asserts the existence of something (absolute space), and says that it has parts, and that bodies move relative to its parts, then that assertion ought to be taken literally. It seems to me unnatural to conclude that he means merely that the laws embody some geometry. That is, even though Newton clearly did understand that 'absolute motion' obtained empirical content from its role in the laws, it is not plausible that the full meaning of absolute concepts in the *Scholium* can be wrung from the laws.

Indeed, it is worth emphasising the elements of the *Scholium* that do not rely on mechanical principles or empirical analysis. The best description of the essay is (drawing on Rynasiewicz 1995a-b) that it lays out mostly – but not exclusively – empirical criteria for a 'philosophical' conception of motion, and shows that certain definitions (notably, Descartes') do not satisfy them; while giving an alternative account that does – motion with respect to absolute space, something with an existence independent of the laws. Then the example of the spheres shows just how such a quantity might be inferred from the phenomena; it is clearly distinguished from the logical role of the earlier examples (including the bucket), and only it can be said to be an empirical analysis of absolute motion as defined.

My point is this: the spacetime framework allows us to understand both how one might define absolute notions without making commitments to any ontological theses, and the nature of some of Newton's insights. But we should not overestimate Newton's insights: because he had some insights into spacetime, it does not follow that he saw how to define absolute quantities without metaphysics.

Following Stein's lead, Earman (1970) also applied the spacetime formalism to clarify Newton and Newtonian mechanics. One important conclusion is that since Newtonian mechanics can be formulated in Newtonian spacetime, which corresponds closely to the properties postulated of absolute space and time, the discovery of Minkowski spacetime alone cannot settle whether Newton was right or wrong. (And given the framework, various theses of 'relationism' can be evaluated.) The use of spacetime here is, then, essentially negative – it shows how little relativity bears on the debate.

Earman reads more into Newton's postulation of absolute space than Stein does. It is a mind-independent 'receptacle', not reducible to the relations of bodies. In his (1989) Earman takes another approach to explicating such a view; spacetime is 'an element of the intended domain of the theory' (a kind of naive realism about geometrical manifolds), or 'a basic object of predication'. In fact, this position was first clearly distinguished by Johnson (1964, but first published in 1922) – the view that bodies not only bear spatial relations to one another, but also to points, he called 'substantival or adjectival'. In that sense, Earman sees Newton as a substantivalist (this is just the kind of view that Stein's Newton puts to one side in the *Scholium*). One might wonder just what hangs on such a thesis, but in much of the recent debate it comes down to whether 'shifts' of the material contents of spacetime relate distinct situations if they preserve the relations between bodies.[6] In Leibniz's famous example, would things have been different if matter had occupied the reflections of the regions it does occupy? According to the substantivalist, the answer is 'yes', because, for instance, Nelson's column would have born the relation of coincidence to a different region of space than it actually does.

It's plausible, though far from certain, that Newton would have endorsed this view (he had the opportunity to deny it via his involvement in the Leibniz-Clarke correspondence, including its publication). Like Stein, Earman sees absolute space as a theoretical postulate, made by Newton in order to formulate his theory. Earman then argues that Newton was correct in his postulation because at the time his theory, formulated in terms of absolute space, was the best explanation of mechanical phenomena. On his reading then, the *Scholium* becomes an abductive argument – the best explanation of the bucket and the globes involves an appeal to absolute space, and so we have inductive grounds to accept it. I've already characterized Newton's argument above, and I think there's no textual support at all for the idea that he had an abductive inference in mind.[7]

So we've seen some of the ways in which the spacetime formalism can clarify the issues arising from Newton's postulation of absolute space – and some of the ways in which it is implicated in mis-understandings of Newton's views. In the remainder of this section I want to argue that the attempt to carry out similar analyses of Newton's contemporaries are even more problematic.

2.2 Other Figures

Another important role for the spacetime formalism is that of explaining the connection between different conceptions of 'relativity' – in particular between relativity in the sense of the symmetry of the laws under co-ordinate transformations and in the sense of the observational indistinguishability of different frames of reference. Friedman (1983) explains how the spacetime formalism provides a framework in which such questions can be posed in a precise way. This work suggests that one can gain insight into early modern views

[6] Naturally, which transformations these shifts are depends both on the geometry of spacetime and what relations hold between bodies.

[7] Of course, if someone had objected to his mechanical theory on the grounds that it required absolute space and time, which were in some way objectionable, then he might well have responded along the lines of *Rule of Reasoning 4*. That is, he would not have given any weight to such speculations until some theory not involving them had been proposed, and which could be compared empirically to his. But it is one thing to give some plausible counterfactual history, and quite another to say what is actually in the *Scholium*.

concerning relativity using the formalism. We have already seen one way in which this idea is problematic even for Newton, with his extremely clear and precise account of relativity: while the co-ordinate symmetries of Newtonian mechanics form the Galilean group, which characterises Galilean spacetime, the observational symmetries are, as Newton proved, wider – they contain the accelerations described in *Corollary VI*.

Things are rather worse for other figures:

1. *Galileo's* 'horizontal' relativity is not even well-defined as far as I can tell, since there are many circles to which an instantaneous motion is tangent.

2. *Descartes'* 'motion properly speaking' is, as Garber (1992) argues convincingly, the definition of motion supposed by his laws. But it is defined (in part[8]) as motion relative to contiguous bodies, and there is no way to capture that notion or the notion of relativity that it embodies in spacetime terms. (Clearly it is not Galilean relativity, and yet it seems that Descartes can agree that the motion of a smoothly moving boat cannot be detected from inside a cabin.)

3. Stein (1977) claims that *Huygens'* views may be clarified by interpreting them in terms of motions in Galilean spacetime, because Huygens has the idea that bodies might have relative motion even if they remain the same distance apart. Other commentators (particularly Earman, 1989) have seen this reading of Huygens as being rather generous, and I am inclined to agree.

4. *Leibniz* was, at one time, seen as possessing the most sophisticated understanding of relativity of his contemporaries – hence his supposed vindication by relativity theory. I want to discuss his views of relativity at length to show that they are profoundly at odds with a modern understanding, and as a result are quite inimical to a spacetime formalisation – his understanding of relativity is much further from the modern one than Newton's.[9]

The natural understanding of Leibniz's doctrine of the 'equivalence of hypotheses' is that he intends a 'general' principle of relativity: *the indistinguishability of a frame from any other, whatever motion it may have.* Such a principle fits a number of things that he says, and is in accord with his stated views that motion is nothing but a relation. However, there are a number of problems. First, only phenomenal or mechanical motion is merely relative; in reality, motion also involves 'derivative active force'. Since force is quantified by mass $\times$ speed^2, several commentators have argued plausibly that fundamentally, far from motion being relativistic, a unique motion can be assigned to each body.[10] So at

[8]The other part of the definition is the requirement that the ambient bodies not be in turbulent motion.

[9]The following discussion is drawn from Huggett (2006b)

[10]Force only associates a speed with each body, and velocities (or equivalently, a privileged rest-frame) can only be inferred from the speeds of a sufficient number of bodies in the right kinds of relative motions. Thus it would be somewhat misleading even to characterise Leibniz's metaphysical view of motion in terms of a spacetime in which velocities are well-defined; the picture is contingent on the arrangement of bodies.

very least we have to bear in mind that another understanding of motion, one that is not relativistic, is in play; we cannot simply appeal to the relational account of motion, even in understanding mechanics, since it is grounded in the deeper notion.

On the other hand, active force is Aristotelian form for Leibniz; as a mechanical philosopher he cannot allow it to play any direct role in mechanics – indeed, that seems to be *the main motivation for the equivalence of hypotheses*.

Even more saliently, Leibniz's laws of collision manifestly do not satisfy a general principle of relativity, but are Galilean relativistic, just like Newton's and Huygens'; to my mind it is inconceivable that this fact could have escaped Leibniz's attention. Indeed, on the occasions on which Leibniz expresses the equivalence of hypotheses most clearly and precisely, the formula is usually that we cannot, on the basis of collisions, determine which body was in motion initially. But this statement (taking 'motion' to mean velocity) is nothing but Galilean relativity.

However, Leibniz also says that rigidly rotating systems would violate the equivalence of hypotheses. But Newton's *Corollaries V-VI* make clear that such a motion does not permit determination of the velocity of the system – such rotations are compatible with Galilean relativity. But while this passage shows that Leibniz did not have Galilean relativity in in mind, it is not convincing evidence that he held general relativity instead. For his explanation of why the equivalence of hypotheses stands is that curvilinear motions are composed of linear ones.

Suppose, as is often suggested, he intends an argument from composition: 'because different states of constant linear motion are indistinguishable, and because curvilinear motions are composed of linear motions, a system's state of curvilinear motion cannot be determined'. This argument commits a glaring fallacy – a charitable reading will find some other understanding of his argument, and hence quite possibly, *of his conclusion*.

What is needed is an interpretation that respects Leibniz's recognition of the Galilean relativity of mechanics, and which makes sense of his argument regarding motion. To that end, look at the *Dynamics* again – Leibniz admits that strictly curvilinear motion would violate the equivalence of hypotheses, thereby implicitly *distinguishing* such motions from 'decomposable' (into linear motions) curvilinear motions. This distinction is not natural to modern ears, but it does solve our puzzle. For two kinds of motion mean two distinct parts to the equivalence of hypotheses: (i) the constant linear motions of bodies cannot be determined and (ii) neither can their strictly curvilinear motions. (i) is what Leibniz refers to when he formulates his laws of collision. (ii) is what he is concerned with when he discusses potential violations of the equivalence of hypotheses. (i) is satisfied because the laws are Galilean relativistic. (ii) is satisfied because there are no strictly curvilinear motions.

The point of course is that if I am at all right in this reading, then there is no natural way to capture Leibniz's views concerning relativity in terms of spacetime; Galilean spacetime is the closest candidate (*pace* footnote 2) but that does not reflect Leibniz's views on curvilinear relativity well. Indeed, the spacetime view has been quite misleading for the interpretation of Leibniz. The spacetime often associated with him is one in which points of spacetime only bear spatial relations to simultaneous points, not to events in the past or future. And this is to attribute to him a view of motion and relativity which is manifestly at odds with his mechanics – since that clearly distinguishes accelerated from non-accelerated motions. It is simply implausible that Leibniz made such an elementary error.

The error that he makes is subtler; he simply fails altogether to give a definition of motion that is appropriate to mechanics. In a sense Leibniz is right when he says to Clarke that nothing in Newton's *Scholium* proves the existence of absolute space – the arguments don't show that Leibniz's metaphysical conception of motion is incorrect. But he misses Newton's point: he still needs an account that will serve in mechanics.

I want to finish my discussion of Leibniz with one remarkable idea – that we should demand that our laws satisfy symmetry principles – the equivalence of hypotheses in particular. Given the role of symmetries in physics of the last 100 years, Leibniz's idea is rather insightful as a methodology. (That said, three points should be taken into account before seeing Leibniz as too prescient: (i) Huygens had already derived laws of collision by applying such a method, and Leibniz may have been reflecting on that; (ii) the reason that Leibniz wants motion to be unobservable is because he identifies it with Aristotelian form – something which a mechanical philosopher cannot allow to play a direct role in mechanics; (iii) because of this source for the idea, the symmetry that Leibniz demands is given *a priori*, unlike many cases in contemporary physics.)

3 Spacetime and Substantivalism

In this section I want to argue, against conventional wisdom, that the spacetime formalism does not help the 'substantivalist's' cause. The kind of argument that I wish to refute was seen in Earman's reading of Newton: we have evidence that spacetime is a substance – in Johnson's sense – because spacetime is involved in the (best) explanation of mechanical phenomena.[11]

The first point to stress is that spacetime geometry is never invoked directly in mechanical explanations – they are not causes of anything in the way that, say, forces are. So, for instance, Sklar's (1974) treatment of the debate gives the argument for substantial spacetime that inertial effects are explained by the universal correlation of such effects with motion relative to the geometric structures of Galilean spacetime. This formulation is at best infelicitous, suggesting a 'fourth law' of Newtonian mechanics explicitly in terms of spacetime geometry. But of course any inertial effects (and the general conditions under which they will occur) can be deduced from Newton's three laws, which make no explicit

[11] In fact, given the thinness of Johnson's conception, perhaps we should define substantivalism instead simply as the doctrine that spacetime is irreducibly involved in mechanical explanations. It is in this sense that DiSalle and I disagree – he says it is, while I say it isn't – though we are both sympathetic to Stein. Thus the debate goes on, 'for better or worse'!

reference to spacetime. Or again, Nerlich (1976) claims that the universality of the first law can only be explained by postulating spacetime geometry – one perhaps imagines something like the 'tracks' along which free particles run. But be careful, again there is only a loose analogy; the explanation of why a train runs along its tracks involves the forces between tracks and train, while nothing analogous is involved in the 'explanation' of inertial motion. I don't claim that either Sklar or Nerlich would dispute the distinction that I'm drawing between mechanical and geometrical explanations. The point I want to make is that while it is generally clear what constitutes an adequate explanation in mechanics, it is not clear at all what the criteria are for explanations of the other kind. Indeed, since putative geometric explanations fall outside of a context like mechanics, it seems to me that no real kind of explaining is going on at all – just a kind of mental comforting.

These considerations have been raised before: for instance, Disalle (1994, 1995), my (1999) and, more recently, Brown (2005). Brown is most concerned with relativity theory, however; in addition to arguing against a geometric explanation of inertia, he also denies that length contraction or time dilation can be explained by the geometry of spacetime. In his view, the first law has no explanation until general relativity, when it can be seen as a consequence of Einstein's equation. Brown calls it a 'miracle' before general relativity, but that description invites the kind of geometrical explanation that he rejects; the first law is no more miraculous than any other law. According to Brown, relativistic effects are also dynamical; not in the sense of 'Lorentzian' dynamics in a preferred frame, but in the sense that the fundamental explanations of why a body has the length it does, and why any process proceeds at the rate it does are in terms of the force laws governing matter – not because of independent spatio-temporal properties of spacetime. I do not have time to investigate here how such views might bear on the issue of substantivalism; rather I want to point out other recent instances of scepticism concerning the explanatory efficacy of spacetime geometry.

Earman is much clearer than Sklar about the abductive argument for substantivalism; for him the point is that spacetime geometry is required for the definitions of the quantities of motion involved in mechanics, and that it seems reasonable to think that the geometry is the geometry of a substantial spacetime. That is, the explanations that provide support for substantivalism are not explanations directly in terms of geometry, but the usual Newtonian mechanical explanations, which supposedly require spacetime in order to be properly meaningful. (This argument should have as much bite in the context of relativistic as non-relativistic mechanics.) There are two kinds of responses available to one who rejects substantivalism. First one could develop an alternative – but empirically adequate – theory to Newton's, in which the only spatio-temporal terms are relations between bodies. Second one could demonstrate that after all, in Newtonian mechanics all spatio-temporal terms – especially motion – can be well-defined without recourse to spacetime.

In the first category are the proposals of Barbour and Bertotti (1982a-b), and of Belot (2000). The following should help give a sense of what is involved. According to Newtonian mechanics there are evolutions that count as distinct possibilities but which do not differ in any relations instantiated: for instance, any body whose parts have no relative motions at all may be rotating at any rate about its centre of mass for suitable centripetal forces. So if a theory attempts to secure empirical adequacy by making predictions in accord with Newtonian mechanics, it will in some sense amount to a proper part of that theory – the part that, for instance, consists of all models with the same total rotation. Time prohibits any real discussion of these views – especially since we are in the presence of someone more authoritative in these matters, and since my own work has taken a different path.

I have recently articulated a view of the second kind (Huggett, 2006), which I would like to sketch here. In the first place, we should understand 'absolute' motion along the lines attributed to Newton by Stein: to be defined in terms of the laws, rather than independently. Following a brief suggestion by van Fraassen (1970), we proceed by formulating Newton's laws 'existentially': 'there exist frames in which the laws (canonically formulated) hold'. Such frames are, by definition, 'inertial frames'; 'absolute' acceleration is, by definition, acceleration in any such frame.

There is a (somewhat) reasonable suspicion that some kind of 'cheating' has gone on – the anti-substantivalist has just stolen the structure that distinguishes inertial motions, without paying the price of substantivalism. Obviously we need something more to raise this gripe to the status of an objection; here are two kinds of worries that might lie behind it.

First, one might wonder whether the construction given actually succeeds in defining absolute motion without even tacit reference to spacetime – either in constructing the necessary frames or in the laws themselves. It is well-known how to construct Euclidean co-ordinates adapted to reference bodies in terms of the spatio-temporal relations of bodies, and then other frames can be defined in terms of suitable transformations of the co-ordinates, none of which involves any reference to spacetime itself. But then the familiar form of the laws contains no explicit mention of spacetime and can be taken as a system of equations in such frames – they can be understood without any reference to spacetime.[12] I don't see that this worry is justified.

Second, it seems correct to say that because the laws are true, the world in some sense has the structure of Galilean spacetime, but in what sense if not a literal one? Of what is it a structure? In my view the best answer is that it is the structure of the systematic relations that bodies bear to one another over time. To put things more precisely, Newton's laws, in the existential formulation, are the simultaneously simplest and strongest axiomatization of the regularities in the relations between bodies. So what I propose is an application of Lewis' (1973) account of laws to van Fraassen's formulation of Newtonian mechanics. To say that the geometry of spacetime is Galilean, is just to say something extremely succinct but extremely powerful about the way that bodies move relative to one another over time.

(In the approach of Barbour *et al* it takes the relations across all space but at only

[12] In terms of the Carnap-Lewis account of theoretical definitions, the construction shows that we can define absolute acceleration using 'o-terms' that do not include any terms referring to spacetime. So doing addresses the hard part of Earman's challenge to the anti-substantivalist; for the rest see Huggett (1999).

one time to fix the state of motion, for the appropriate frame is one in which the total rotation of *everything* vanishes. In mine – for forces that fall off rapidly with distance – local relations over time do it, for it takes time to determine which frames are inertial. Regarding the practical matter of applying the laws to real systems, such as the planets, there is no difference.)

So I believe that the idea that accepting Newtonian mechanics entails, or even tends to, the acceptance of substantival spacetime is completely mistaken – at least for the reasons given by Earman (Friedman, for instance, has another kind of argument). Indeed, I have my doubts whether any robust sense can really be given to the concept that isn't already captured by the account that I have given. It appeared that because the laws have a spacetime formalism one could use one's favourite realist argument to infer that spacetime must exist as an entity distinct from matter. But the formalism, while beguiling, is misleading on this point.

4 Conclusion

In the 'absolute-relative' debate, the spacetime formalism leads in two different directions. First, as Stein showed, it allows us to say precisely what 'structure' is required by Newtonian mechanics – the geometry of Galilean spacetime (ignoring footnote 2). Thus it allows us to define the controversial 'absolute' concepts directly in terms of the laws. Among the dangers along this path we have seen two. On the one hand, one may read this lesson back into Newton; but while (as Stein among others have shown) he certainly had a methodology as sophisticated as his physics, one should be careful not to go too far. On the other, success in understanding Newton's views in spacetime terms encourages trying the same strategy on his contemporaries – even (Earman, 1989) seeing the historical debate in large part as one over the geometry of spacetime. But there are good reasons to think that spacetime geometries are a poor way to capture the views of other natural philosophers.

The formalism also points to the realist-anti-realist controversy (which, not coincidentally, came to the fore at the same time as renewed interest in the absolute-relative debate, in the late 1960s). For the geometrical structures can, mathematically, be understood as objects defined on a manifold of points. The realist is inclined to think that if the geometric structure is a part of physical reality, then so are the points – so space is substantial. But there are at least two reasonable ways of avoiding this line of thought, both showing that the structure can be understood to belong to bodies. First, one can revise the laws of mechanics so that the structure required can manifestly be understood in terms of the relations between bodies at any time; by making absolute total rotation as empty a concept as absolute velocity. Second, one can keep Newton's laws of mechanics but explicate more fully Stein's proposal; show that the structures are structures of the history of material events. These proposals are surely at least as reasonable as substantivalism; the spacetime approach does not vindicate substantivalism at all.

Neither approach banishes geometry: bodies have spatio-temporal properties, and spacetime geometry describes the evolutions of those properties. But that is not to say that spacetime is substantial, or even that the structures are prior to or independent of bodies.

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